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Thermal performance of marketed SDHW systems under laboratory conditions

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Abstract

A test facility for solar domestic hot water systems, SDHW systems was established at the Technical University of Denmark in 1992. During the period 1992-2012 21 marketed SDHW systems, 16 systems from Danish manufacturers and 5 systems from manufacturers from abroad, have been tested in the test facility under the same realistic test conditions. The systems had different designs and sizes. Each system was tested during a long test period consisting of both a summer and winter period.

Detailed simulation models for each system were developed. The simulation models were modified and the input to the models were fitted in such a way, that the calculated thermal performance is in good agreement with the measured thermal performance, both for a typical winter period and for a typical summer period. In this way it is possible to use the simulation models to calculate the yearly thermal performance of the tested systems with weather data from the Danish Test Reference Year and with the same hot water consumption.

The tests showed that the designs of the heat storage and that the system concepts are of vital importance for the thermal performances of the systems and that neither the solar collector efficiency nor the solar collector area is influencing the thermal performance as much as the heat storage design and the system concept. The tests also showed that all the tested systems can be improved with relative simple design changes.

Based on the tests it is concluded that high thermal performances of SDHW systems are achieved by reducing the heat loss from the upper part of the heat stores to a minimum by having no pipes connected to the upper part of the tank, reducing the auxiliary volume at the top of the heat stores as much as possible, of course with consideration of the required hot water comfort, avoiding simple errors, using the low flow principle and heat stores with a high degree of thermal stratification and by using components with good thermal characteristics.

1. Introduction

Direct comparisons of the thermal performances of different SDHW systems are possible if the SDHW systems are tested side-by-side under the same realistic conditions in a laboratory test facility. Measurements from side-by-side tests of marketed SDHW systems in a laboratory test facility are therefore useful for manufacturers in connection with their considerations whether or not improvements of their systems are needed.

The basis for development of improved SDHW systems is detailed knowledge of the thermal behaviour and of the thermal performances of components and systems under different operation conditions. This knowledge is achieved by tests of the systems.
In connection with development of cost efficient SDHW systems it is important to know how different changes of the design of the systems will influence the thermal performance of the systems. It is

therefore important that the systems are tested under realistic conditions in such a way that the measurements can be used to validate detailed simulation models for the systems. By means of the validated simulation models the yearly thermal performance of differently designed SDHW systems can be determined with weather data from the Danish Test Reference Year. Such calculations are together with cost evaluations an excellent basis for manufacturers in their efforts to develop improved marketed SDHW systems.

2. Test facility and test conditions

A test facility for SDHW systems in which 8 small SDHW systems for one family houses can be tested side-by-side under the same realistic conditions was established in 1992 at the Technical University of Denmark. The solar collectors of the systems are placed on a stand facing south or on a roof of a test hall oriented 10° towards west from south. The collector tilt from horizontal is 45°. The hot water tanks of the systems are placed inside the test hall at a temperature of about 15°C-20°C. The total length of the solar collector loops are about 26 m. Figure 1 shows collectors on the stand and hot water tanks in the test hall.

Fig. 1. Solar collector stand and hot water tanks in test hall.

Hot water is tapped 3 or 4 times a day in equally large energy quantities. Draw off takes place in the morning, at noon and in the evening corresponding to a realistic draw-off pattern. During each draw off a specific energy quantity is tapped from the hot water tanks, corresponding to a daily hot water consumption of either 100 l or 200 l heated from 10°C to 50°C or 45°C. The temperatures in the top of the hot water tanks are maintained at a set-point temperature of 50.5°C or 50.0°C by means of the auxiliary energy supply system.

Four temperatures in the solar collector loop, the domestic cold and hot water temperatures and temperatures in different levels of the hot water tank are measured. Further, in periods where the top of the tank is heated by an auxiliary energy supply system by circulation of water through a heat exchanger spiral placed at the top of the tank, forward and return temperatures to and from the heat exchanger spiral are measured. The following energy quantities are measured: Solar heat transferred to the hot water tank, auxiliary energy transferred to the hot water tank, energy tapped from the tank and the energy consumption for the circulation pump in the solar collector loop and the control system. Finally, the total solar irradiance and the diffuse irradiance on the solar collectors as well as the ambient air temperature and the indoor air temperature in the test hall are measured.
Each system has been tested for a long period of more than one year.

3. Tested systems

During the last 20 years 21 marketed SDHW systems, 16 systems from Danish manufacturers and 5 systems from manufacturers from abroad, have been tested in the laboratory test facility under the same test conditions [1-6], see table 1. The systems had different designs, collector types, collector efficiencies and collector areas in the interval from 2.51 m² to 5.56 m². Further, the systems had different heat storage volumes in the interval from 180 l to 470 l. The Danish systems were installed by the manufacturer's installers, and the foreign systems were installed by the staff of the Technical University of Denmark. Most of the systems are high flow systems making use of a spiral tank, that is a tank with a built in heat exchanger spiral in the lower part of the tank. The solar collector fluid is with a high volume flow rate circulated through the heat exchanger spiral. In this way solar heat is transferred from the solar collector to the tank. A number of the systems are low flow systems making use of a mantle tank. In these systems the solar collector fluid is with a low volume flow rate circulated through a mantle welded around the lower part of the tank. In this way solar heat is transferred to the tank.

It must be mentioned, that a number of the tested systems are not any longer marketed and that some of the manufacturers are not active in the solar heating field today.

Detailed simulation models for all the systems were developed. The simulation models were modified and the input to the models were fitted in such a way, that the calculated thermal performance is in good agreement with the measured thermal performance, both for a typical winter and summer period. In this way it is possible to use the simulation models to calculate the yearly thermal performance of the tested systems with weather data from the Danish Test Reference Year, with the same hot water consumption and with the same set-point temperature for the auxiliary energy supply system.

4. Thermal performances of tested systems

Calculations with the above mentioned validated simulation models were used to determine the yearly thermal performances of the systems under standard conditions. That is: The daily hot water consumption is 200 l heated from 10°C to 45°C, the auxiliary energy supply system - if included in the tank - heats the top of the hot water tank to 45.5°C and the weather data from the Danish Test Reference Year is assumed. The yearly hot water consumption is 2940 kWh. Table 2 shows for each system the calculated yearly net utilized solar energy, the yearly net utilized solar energy per m² solar collector and the yearly solar fraction. The net utilized solar energy is defined as the energy tapped from the tank - auxiliary energy. The solar fraction is defined as the ratio between the net utilized solar energy and the energy for hot water consumption. The yearly net utilized solar energies for the systems are situated in the interval from 1035 kWh to 1805 kWh, corresponding to solar fractions between 35.2% and 61.4%. The yearly net utilized solar energies per m² solar collector for the systems are situated in the interval from 271 kWh/m² to 535 kWh/m².

It is noticed that the two Swiss low flow systems, in spite of the relatively small collector areas of 4.20 m² and 4.36 m², have the highest thermal performances of the tested systems. The yearly thermal performances of the Swiss systems are 7%, respectively 8%, higher than the yearly thermal performance of the system with the third highest thermal performance, the system from Arcon Solvarme. This in spite of the fact, that the solar collector areas of the Swiss systems are 16%, respectively 13%, smaller than the collector area of the Arcon Solvarme system. Further, the thermal performance of the solar collector from Arcon Solvarme is higher than the thermal performances of the Swiss solar collectors. For instance, figure 2 show the efficiency of the solar collectors from Bürgenmeier-Krismer and from Arcon Solvarme for a solar irradiance of 800 W/m² and an incidence angle of 0° and the calculated thermal performance of the two collectors for an incidence angle of 0° and for solar irradiances of 400 W/m² and 800 W/m².

Table 1. Main characteristics of 21 tested SDHW systems.

Manufacturer	**Test period**	**Solar collector area m²**	**Heat storage type**	**Heat storage volume l**	**Auxiliary energy supply system in heat storage**	**Characteristics**
Dansk Solvarme 1	1993	4.00	Spiral tank	290	El & Hx	High flow system
Batec Solvarme 1	1993	4.38	Spiral tank	295	El & Hx	High flow system
Thermo Dynamics Ltd., Canada	1994	5.56	Hot water tank with external heat exchanger	270		Low flow system Preheating system Lifeline
ZEN B.V., the Netherlands	1994	2.70	115 l preheating tank with built in solar heat exchanger spiral, 120 l hot water tank and 20 l drain back tank	255	El	High flow system Drain back
Bürgenmeier-Krismer Solartechnik, Switzerland	1994-1997	4.36	276 l hot water tank in a 129 l unpressurized tank	405	El	Low flow system Flextube
Aidt Miljø	1995	4.83	Mantle tank	265/16	El & Hx	Low flow system
Dansk Solvarme 2	1995	4.02	Spiral tank	280	El & Hx	High flow system
Batec Solvarme 2	1995	4.38	Mantle tank	250/50	El & Hx	Drain back Low flow
Arcon Solvarme	1995	5.02	Spiral tank	250	El & Hx	High flow system
Solahart Scandinavia 1	1995	5.55	Spiral tank	280	El & Hx	High flow system
Thermo-Sol	1995	3.33	Spiral tank	280	El & Hx	High flow system Evacuated tubular collectors
Sol-Energi Kobbervarefa-brikken	1995	3.82	Spiral tank	280	El & Hx	PV powered pump
Nordsol	1996	4.02	Mantle tank	265/12	El & Hx	Low flow system
Solahart Scandinavia 2	1997	3.70	Mantle tank	265/12	El & Hx	Low flow system
SolarNor, Norway	1997	5.48	Spiral tank	285	El	High flow system Drain back
Batec Solvarme 3	1999	4.38	Spiral tank	280	El & Hx	High flow system
AquaHeat	2002	2.72	Mantle tank	152/28	El & Hx	Low flow
Hoval-Solkit, Switzerland	2002	4.20	Tank with two mantles	470	El & Hx	Low flow system Flextube
Velux	2008	4.30	Spiral tank	300	El & Hx	Variable flow rate in solar collector loop
Batec Solvarme 4	2008	4.38	Spiral tank	280	El & Hx	High flow system
Solvarmebehol-deren.dk	2011-2012	2.51	Stainless steel mantle tank	165/21	El	Low flow system

El: Electric heating element. Hx: Heat exchanger spiral

Table 2. Thermal performance of 21 tested SDHW systems for standard conditions.

Manufacturer	**Solar collector area m²**	**Net utilized solar energy kWh/year**	**kWh/m² year**	**Solar fraction %**
Dansk Solvarme 1	4.00	1353	338	46.0
Batec Solvarme 1	4.38	1453	332	49.4
Thermo Dynamics Ltd., Canada	5.56	1643	296	55.9
ZEN B.V., the Netherlands	2.70	1308	484	44.5
Bürgenmeier-Krismer Solartechnik, Switzerland	4.36	1792	411	61.0
Aidt Miljø	4.83	1345	278	45.7
Dansk Solvarme 2	4.02	1472	366	50.1
Batec Solvarme 2	4.38	1492	340	50.7
Arcon Solvarme	5.02	1671	333	56.8
Solahart Scandinavia 1	5.55	1548	279	52.7
Thermo-Sol	3.33	1545	464	52.6
Sol-Energi Kobbervarefabrikken	3.82	1035	271	35.2
Nordsol	4.02	1458	363	49.6
Solahart Scandinavia 2	3.70	1455	393	49.5
SolarNor, Norway	5.48	1357	248	46.2
Batec Solvarme 3	4.38	1508	344	51.3
AquaHeat	2.72	1326	488	45.1
Hoval-Solkit, Switzerland	4.20	1805	430	61.4
Velux	4.30	1258	293	42.8
Batec Solvarme 4	4.38	1603	366	54.5
Solvarmebeholderen.dk	2.51	1344	535	45.7

The efficiency of the solar collector from Arcon Solvarme is somewhat lower than the efficiency of the collector from Bürgenmeier-Krismer. However, the calculated thermal performance of the collector from Arcon Solvarme is due to the large collector area higher than the calculated thermal performance of the collector from Bürgenmeier-Krismer. Consequently, the high thermal performance of the Bürgenmeier-Krismer system is not caused by the solar collector efficiency or the solar collector area.

The thermal performances of the Swiss systems are high because the upper parts of the heat storages have no thermal bridges of importance, because a high degree of thermal stratification is built up in the heat storages due to the design of the heat storages and due to the low volume flow rates in the solar collector loops and because the heat losses from the solar collector loops are small due to the use of small well-insulated flexible silicone tubes.
Further, the investigations showed that the designs of the heat storage are of vital importance for the thermal performances of the systems. For instance, the heat losses from the upper part of the hot water tanks for most of the systems are much larger than expected due to penetrations through the insulation material. These thermal bridges result in strongly reduced thermal performances. For most of the hot water tanks the penetrations are caused by pipe connections and electric heating elements.

5. Evaluation of thermal performances

It is difficult to evaluate if the thermal performances of the systems are as high as expected since both the collector area and the collector efficiency vary from system to system. Investigations have shown that there is no connection between the calculated power of the solar collectors and the measured thermal performance of the systems [1]. Consequently, the collector efficiency and the collector area are not of vital importance for the thermal performances of the systems.

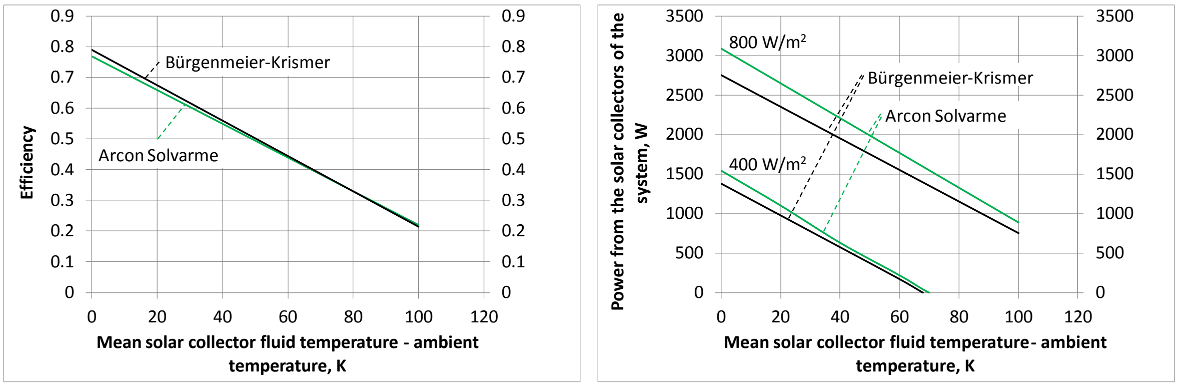

Fig. 2. Left: Efficiency for solar collectors from Bürgenmeier-Krismer and Arcon Solvarme for a solar irradiance of 800 W/m² and an incidence angle of 0° as a function of the difference between the mean solar collector fluid temperature and the ambient air temperature. Right: Calculated powers from solar collectors for solar irradiances of 800 W/m² and 400 W/m² and an incidence angle of 0°.

Figures 3-5 show the yearly net utilized solar energy per m² solar collector as a function of the yearly solar fraction for the 21 systems. The two systems with the highest yearly net utilized solar energy per m² collector are the systems from Solvarmebeholderen.dk and AquaHeat. Both systems are low flow systems with mantle tanks and a relatively small solar collector area and solar fraction. In order to compare the thermal performances of the systems with the thermal performances of different standard systems, calculated thermal performances of a number of standard solar heating systems are also shown on the figures. The standard system is based on a vertical cylindrical steel tank with a built in heat exchanger spiral transferring solar heat from the solar collector fluid to the domestic water. The heat exchanger spiral is located at the bottom of the tank. The tank is insulated with 5 cm PUR foam. The tank volume is 280 l, and the upper 52 l of the tank is heated to 45.5°C by the auxiliary energy supply system. The volume flow rate in the solar collector loop is 1 l/min per m² collector.

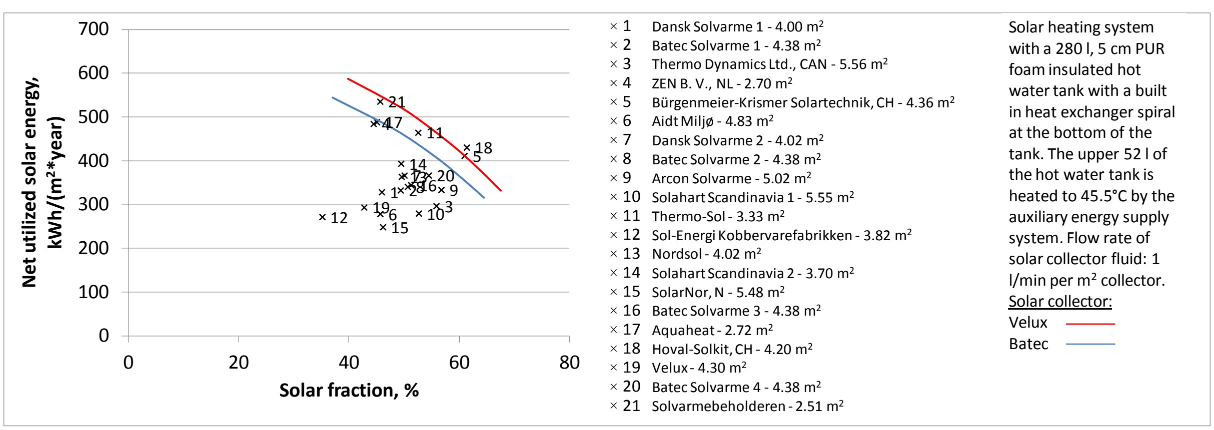

Fig. 3. Yearly net utilized solar energy per m² solar collector for the 21 systems. The curves show calculated yearly net utilized solar energy per m² solar collector for the standard system with two different solar collectors.

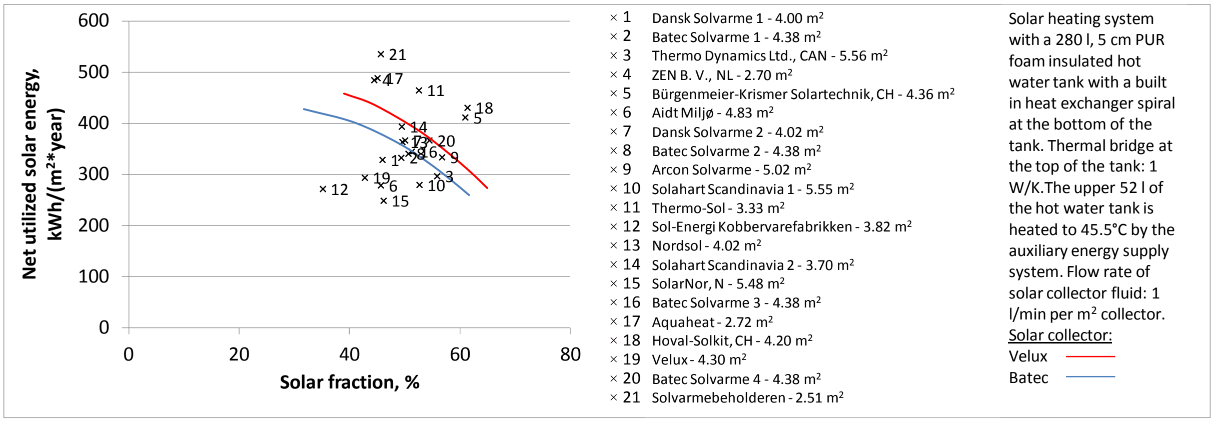

Fig. 4. Yearly net utilized solar energy per m² solar collector for the 21 systems. The curves show calculated yearly net utilized solar energy per m² solar collector for the standard system with a thermal bridge at the top of the tank of 1 W/K. Calculations are carried out with two different solar collectors.

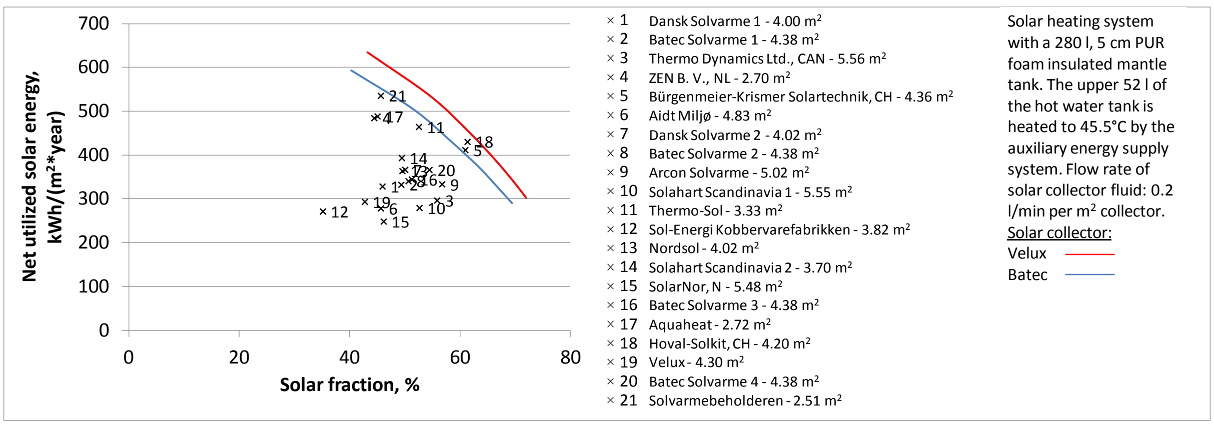

Fig. 5. Yearly net utilized solar energy per m² solar collector for the 21 systems. The curves show the calculated yearly net utilized solar energy per m² solar collector for standard low flow systems with a mantle tank.

The calculations are carried out with two collectors, a collector with a normal cover glass from Batec, BA22 and a collector with an antireflection treated cover glass from Velux, CLI U12 5000, [7-8]. For the Batec collector the maximum efficiency is 0.767 and the first and second order heat loss coefficients are 3.867 W/m²K and 0.0100 W/m²K². For the Velux collector the maximum efficiency is 0.821 and the first and second order heat loss coefficients are 3.286 W/m²K and 0.0173 W/m²K². The incidence angle modifier is 0.95 for an incidence angle of 50° for both collectors.The performance curves in figure 3-5 are shown for these two collectors by changing the collector area and by that the solar fraction. From figure 3 it is obvious that the thermal performances of most of the tested systems are relatively low. Only the thermal performances of the two Swiss systems and the system from Solvarmebeholderen.dk are relatively high. Figure 4 shows the thermal performances of the same standard systems, now with a thermal bridge of 1 W/K situated at the top of the tank. Such a thermal bridge strongly reduces the thermal performances of the systems. Most of the tested systems' hot water tanks have relatively high heat losses. This is the main reason for the relatively small system performances. Figure 5 shows the thermal performances of standard low flow systems based on a standard mantle tank. The thermal performance is increased due to the low flow principle and the high degree of thermal stratification established in the heat storage during solar collector operation. 8 of the tested systems are low flow systems. The thermal performances of all these systems are lower than the thermal performance of the standard low flow systems based on the Velux solar collector. Consequently there are good possibilities of improving the designs of all the tested systems with increased thermal performances as a result.

6. Conclusions and recommendations for SDHW design and for research and development

The tests showed that the designs of the heat storage and that the system concepts are of vital importance for the thermal performances of the systems and that neither the solar collector efficiency nor the solar collector area is influencing the thermal performance as much as the heat storage design and the system concept. The tests also showed that all the tested systems can be improved with relative simple design changes.

Based on the tests it is concluded that high thermal performances of SDHW systems are achieved by reducing the heat loss from the upper part of the heat stores to a minimum by having no pipes connected to the upper part of the tank, avoiding simple errors, using the low flow principle and heat stores with a high degree of thermal stratification, using components with good thermal characteristics and by reducing the auxiliary volume at the top of the heat stores as much as possible, of course with consideration of the required hot water comfort.

Based on the investigations it is recommended to carry out research and development on optimum designed low flow systems based on components specifically suitable for low flow operation. The focus must be on optimal designed mantle tanks, flexible solar collector loops with two tubes with low heat losses and low heat exchange between the tubes, advanced small low flow pumps/control systems with a low power consumption and variable volume flow rate, drain back systems with water as solar collector fluid and on smart mantle tanks with a variable auxiliary volume - fitted to the expected coming hot water consumption and solar heat production - heated by the auxiliary energy supply system.

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